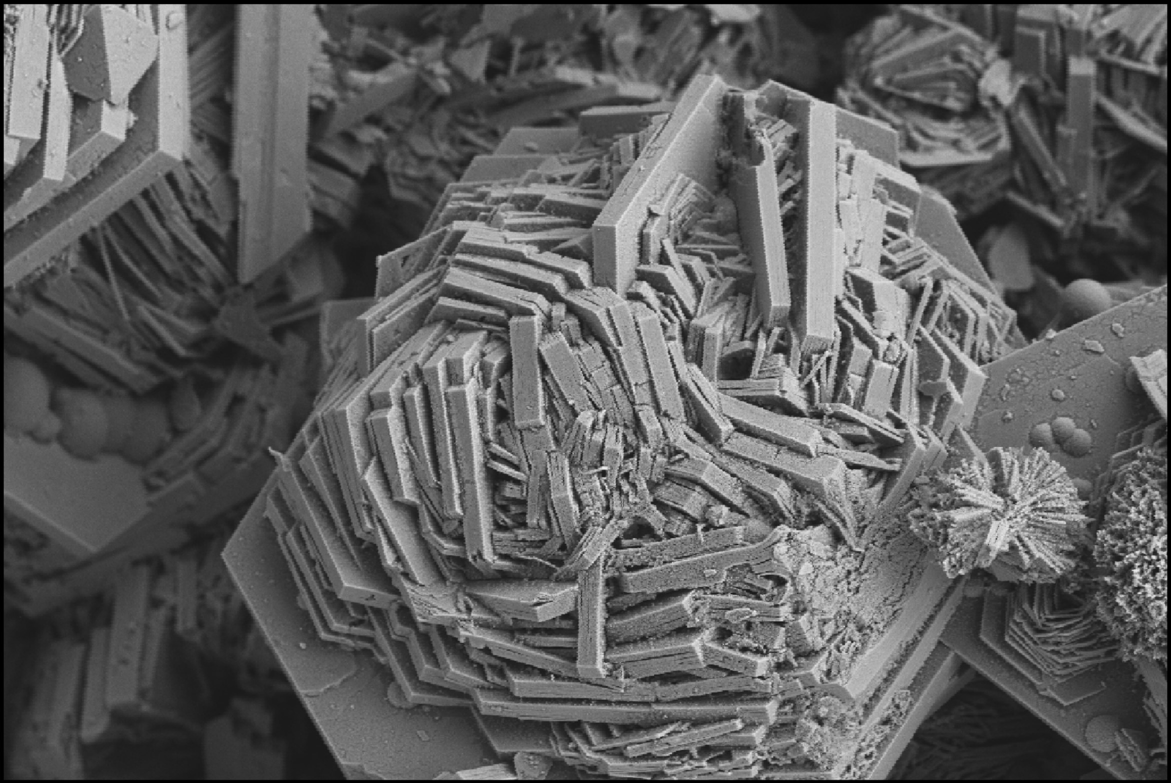
Habitability in Saline Environments on Mars



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The Ancient Martian Surface: How Habitable?

- **To what extent can we generalize?**
  - On Mars, like Earth, water is the only game in town...

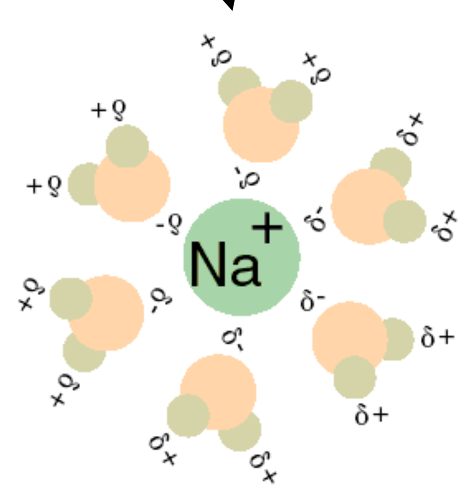
- **Some controls on the limits of terrestrial life:**
  - Temperature
  - Radiation
  - Acidity
  - Temporal availability of water
  - Salinity (water activity)

- **Define habitability in an *evolutionary* context**
  - Prebiotic chemistry & the *origin* of life
  - Evolution and/or adaptation to changing surface chemistry

Water Activity (a_{H2O})

- **A thermodynamic measure of salinity**
  - Water is chemically unavailable at high solute concentration
  - Increasing salinity decreases water activity

$$\ln a_{H_2O} = \frac{\phi(\sum \nu_i m_i) M_w}{-1000}$$



Selected Water Activity Values

Pure water	1.00
Average river water	0.99
Seawater	0.98
Halite (NaCl) saturation	0.75

- **Sharp a_{H2O} limitations on biological activity**

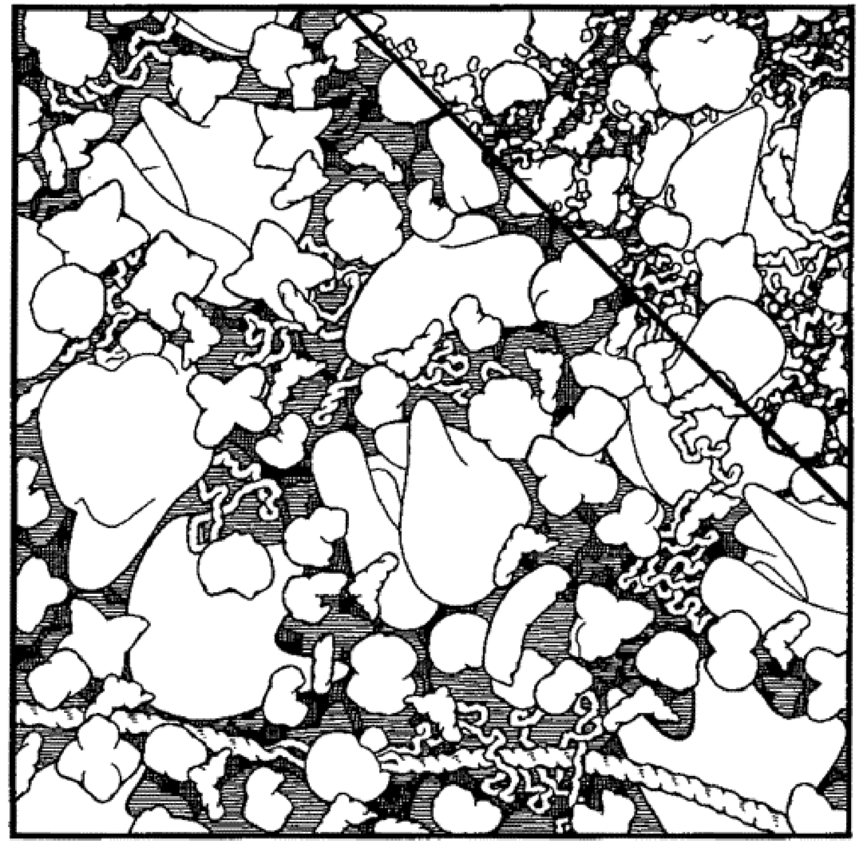
a_{H2O}: Limits on terrestrial life

- **Microbial strategies for low a_{H2O} conditions:**
  1. Synthesize "compatible solutes" (e.g., glycine, betaine)
  2. Increase salt content of cytoplasm

     (Evolutionary processes)

- **Biochemical consequences of high salinity (low a_{H2O})**
  – Inhibition of protein folding
  – Bio-molecule denaturation & functionality loss

- **What are the numerical limits?**



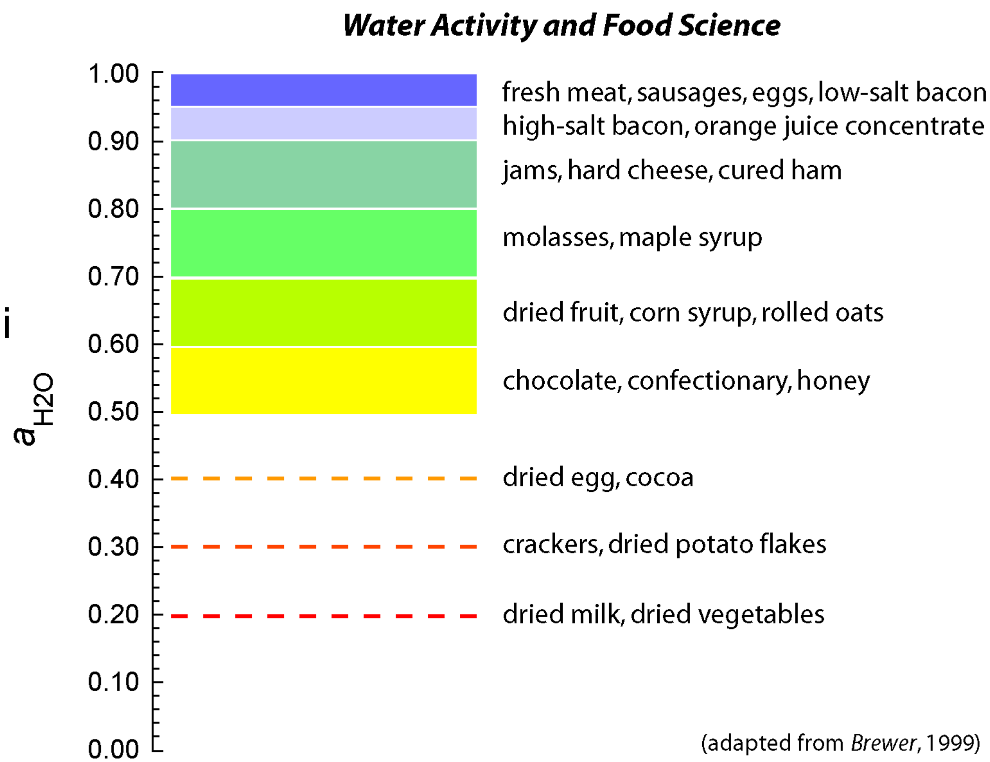
Cytoplasm, from *Goodsell (1993) The Machinery of Life.*

a_{H2O}: Limits on terrestrial life

a_{H2O} ~ 0.90:
- Limit for most organism growth

a_{H2O} ~ 0.75:
- Limit for most extremophilic fungi & archaea

a_{H2O} = 0.61:
- Effective habitability limit
- *X. Bisporus* in high-sugar food



- **~175 of 10^7 known species exhibit halo-tolerance / halo-philism**
- **Regardless of the precise number, limits provide useful benchmarks**

Calculating a_{H2O} for Martian Systems

1. **Constraints on dilute fluid chemistry**
   - Experimental weathering studies
2. **Thermodynamic model for highly saline waters**
3. **Data on mineral solubility**
4. **Martian saline assemblages**

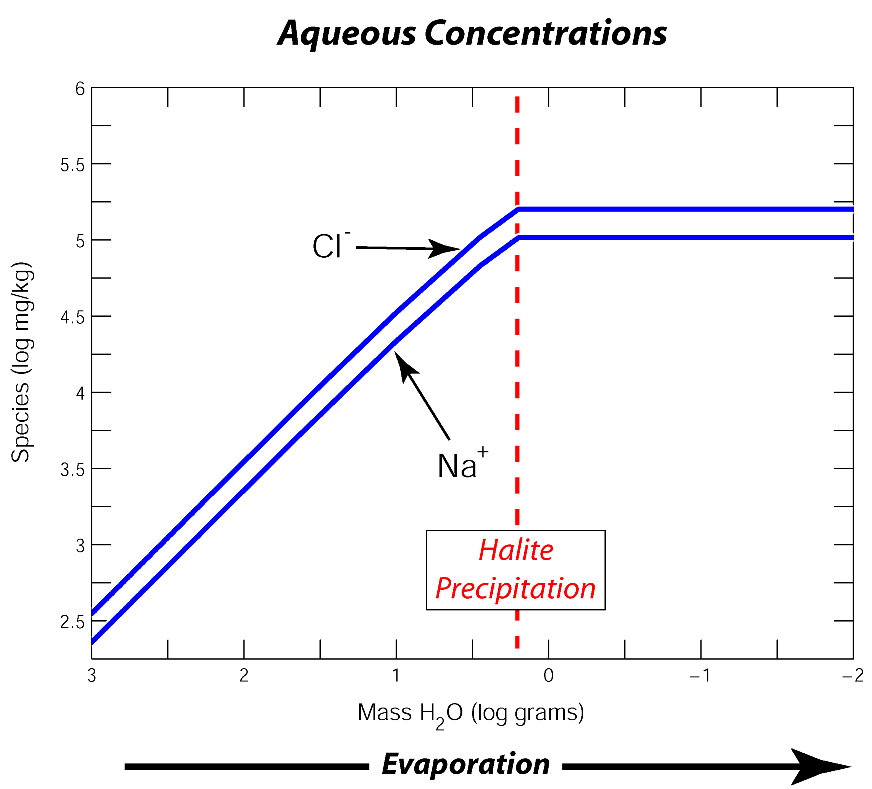
Thermodynamic simulation of evaporation yields *osmotic coefficient* (calculated with Pitzer equations)

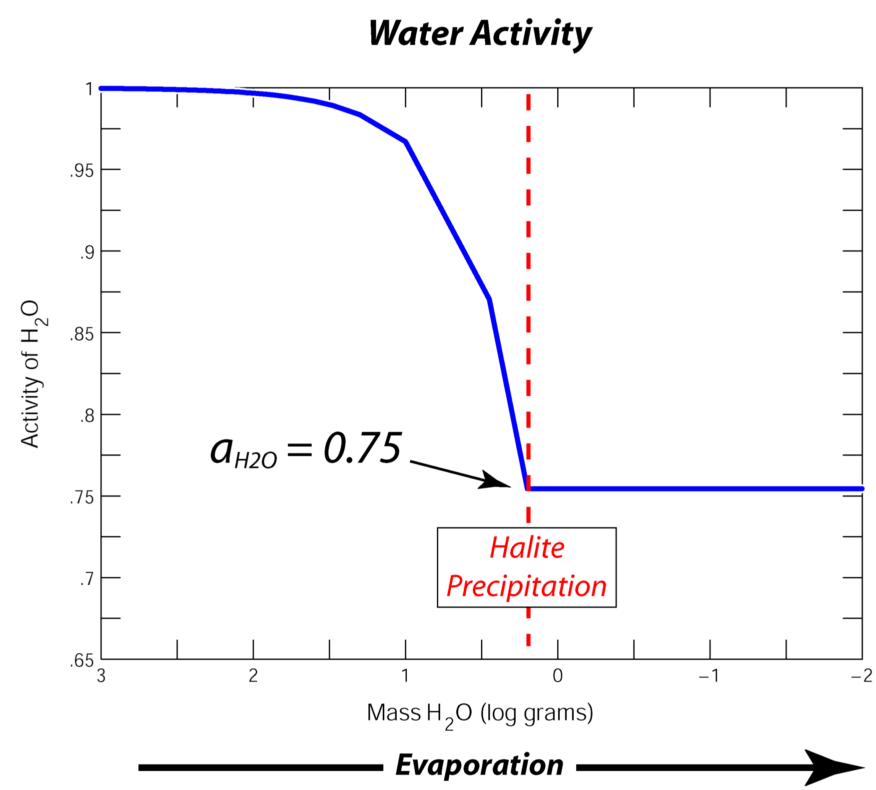
Water activity is proportional to the *osmotic coefficient*

$$\ln a_{H_2O} = \frac{\phi(\sum \nu_i m_i) M_w}{-1000}$$

***Goal:* For a martian water, calculate a_{H2O} at the point of saline mineral precipitation**

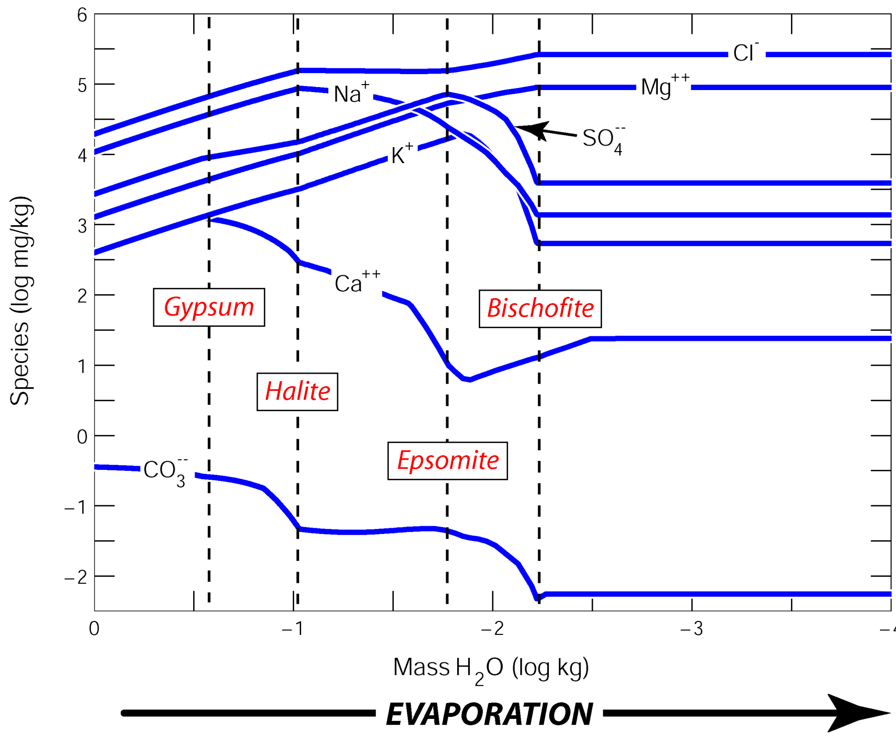
Mineral Precipitation and a_{H2O}



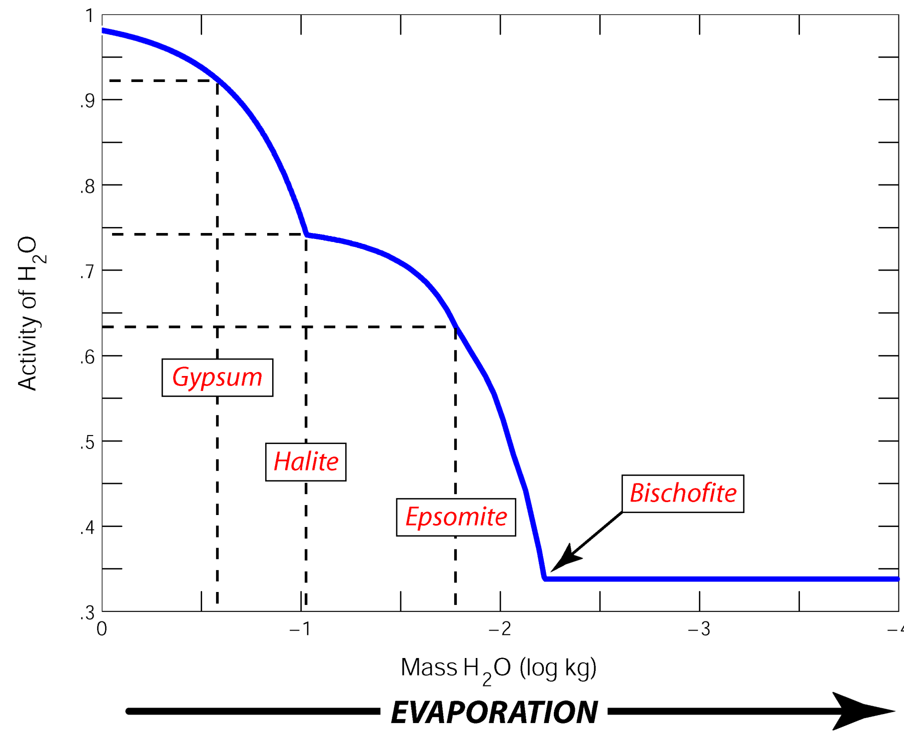


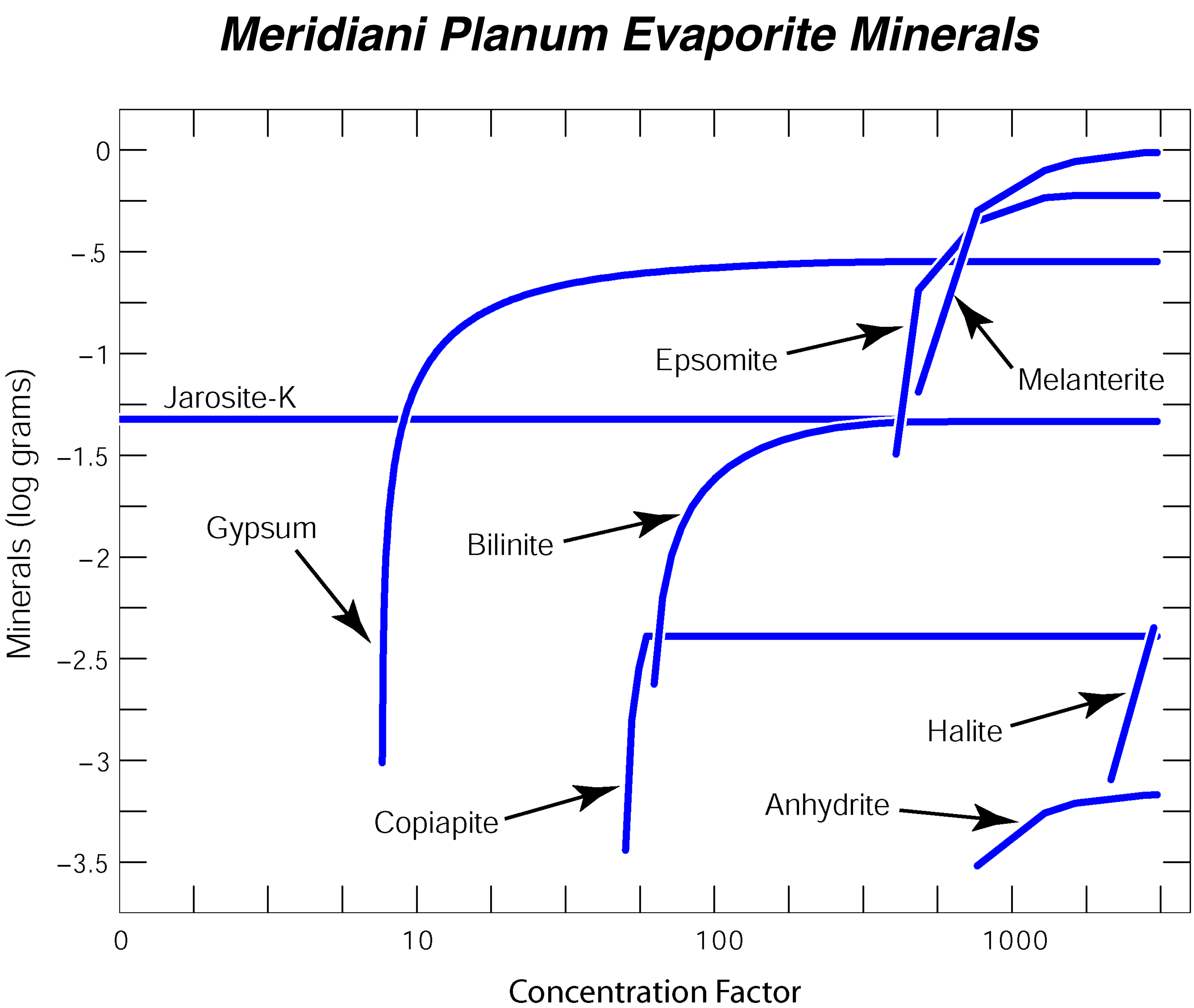
a_{H2O} and Seawater Evaporation

Aqueous Concentrations



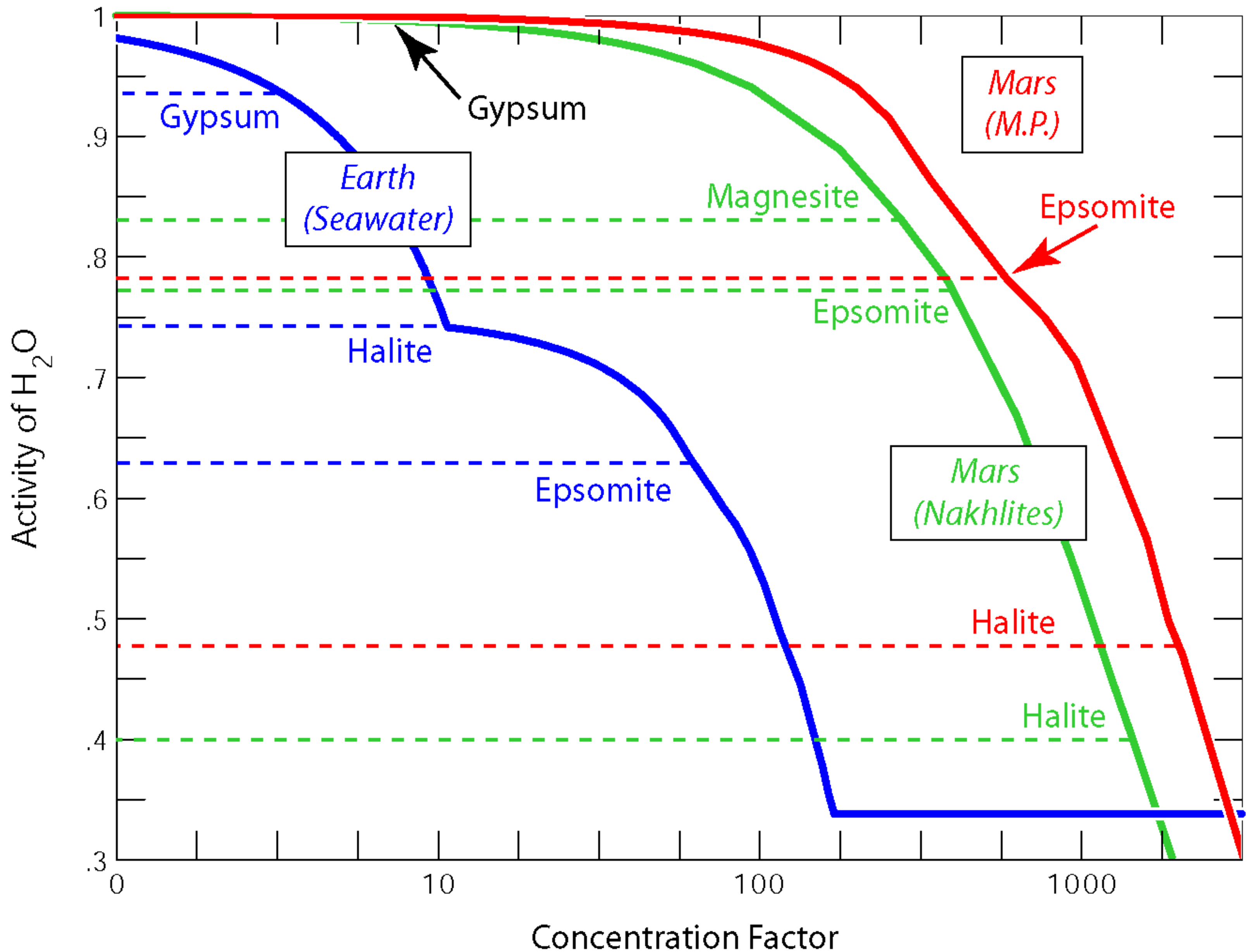
Water Activity

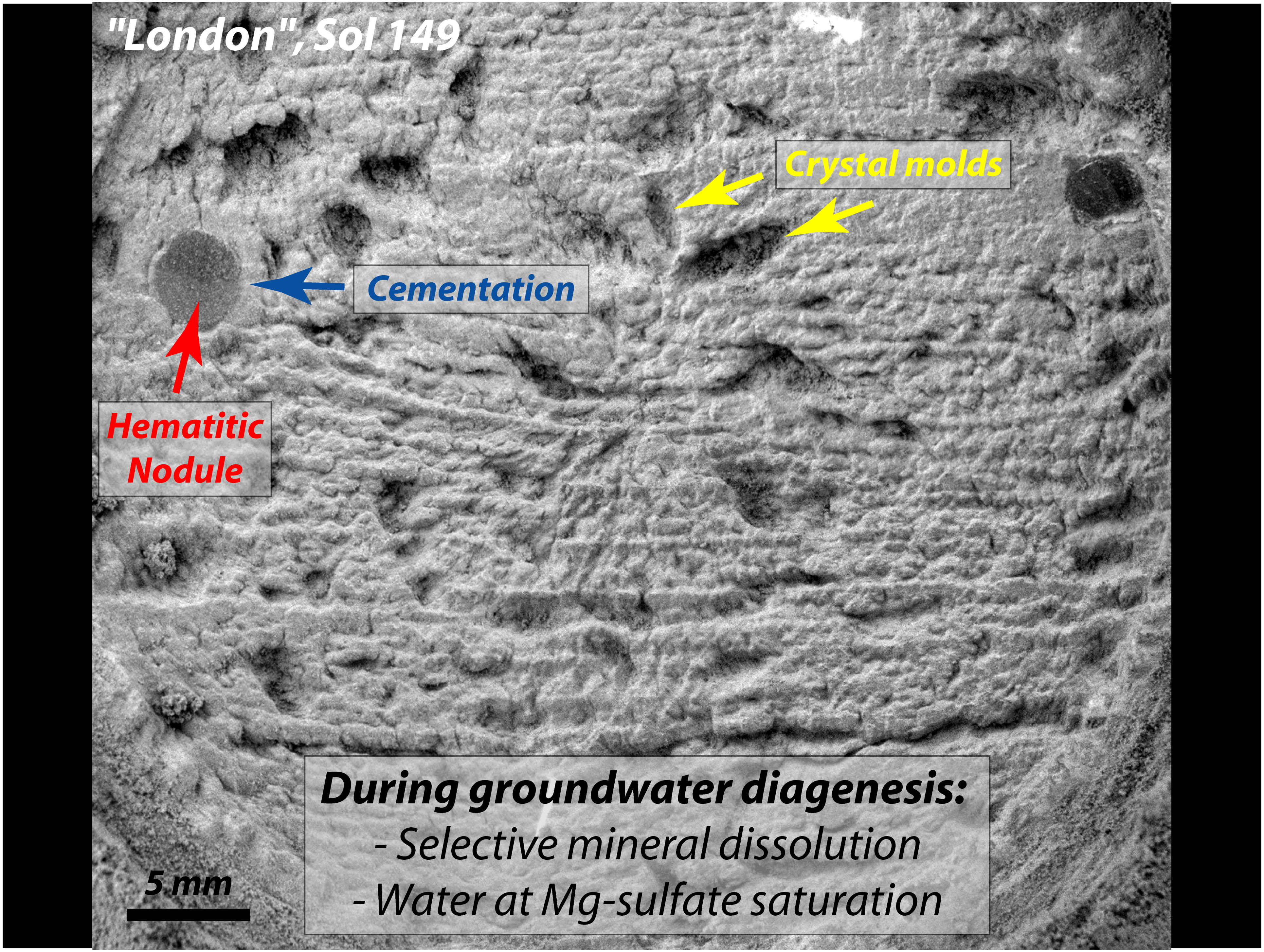




Meridiani Planum Evaporite Minerals
Minerals (log grams)
Concentration Factor
0
-.5
-1
-1.5
-2
-2.5
-3
-3.5
0
10
100
1000
Jarosite-K
Gypsum
Bilinite
Epsomite
Melanterite
Halite
Anhydrite
Copiapite

Water Activity on Mars




"London", Sol 149
Crystal molds
Cementation
Hematitic Nodule
5 mm
During groundwater diagenesis:
- Selective mineral dissolution
- Water at Mg-sulfate saturation

a_{H2O}: General Mineralogical Trends

- **Chlorides reflect distinctly low a_{H2O} (<0.50)**
  - Function of sulfate vs. chloride solubility
  - Insensitive to SO_4/Cl ratio of initial water
- **Gypsum & carbonates are "insoluble" & reflect high a_{H2O} (~0.95)**
- **All Mg-, Fe^{2+}-sulfates reflect low a_{H2O} (~0.78 and lower)**
- **Fe^{3+}-sulfates (exclusive of jarosite & schwertmannite) reflect both low a_{H2O} and low pH**
  - Include ferricopiapite, copiapite-group minerals, rhomboclase, etc.

Low a_{H2O}: A Challenge for Life on Ancient Mars

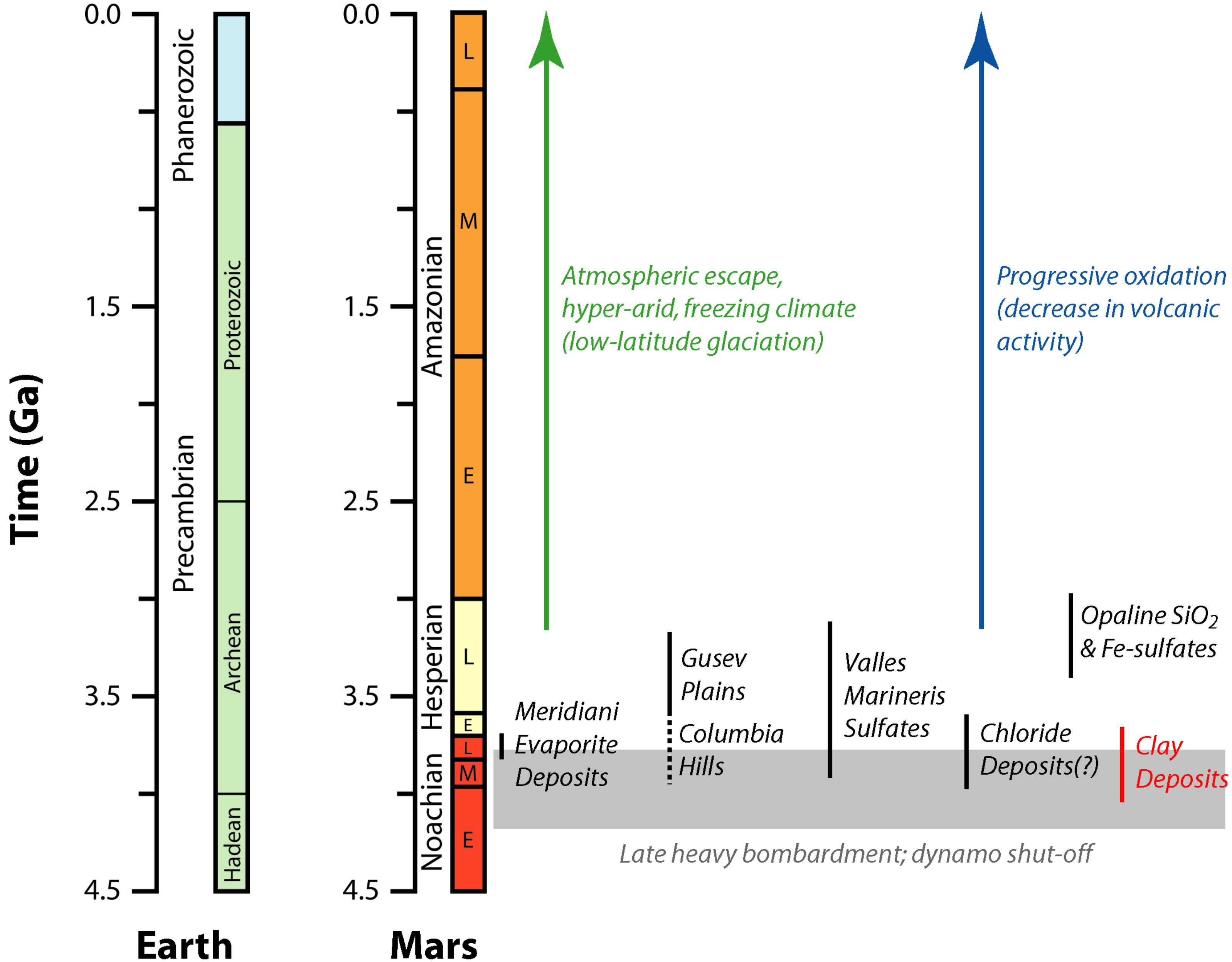
- **Distinction between *originating in* & *adapting to* low a_{H2O}**
- **Halo-tolerance/philism is evolutionary**

Selected Water Activity Values

Epsomite at Meridiani Planum	0.78
Halite at Meridiani Planum	0.51
SNC Meteorite Brines	0.40
Paso Robles Soil Brines	0.61
Limit for most organism growth	~0.90
Limit for most extremophilic fungi & archaea	~0.75
Effective "habitability limit" (*X. bisporus*)	0.61

- **Low a_{H2O} and pH prohibit pre-biotic reactions**
  - There must be numerical limits & they provide useful benchmarks
- **Where are the dilute fluids?**
  - Are we seeing snapshots as Mars evaporated to dryness?
  - Is this representative of H_2O-limited processes?
- **Window of habitability was short and occurred early**

Relative Timing



Origin, Evolution & Preservation

On a local/regional scale:

- **Need Favorable "pre-biotic" chemistry**
  - Reducing conditions
  - "Mild" pH
  - Highest possible a_{H2O}
- **Maximum temporal availability of water**
  - Sustained versus episodic
- **Optimal preservational (post-depositional) characteristics**
  - *Less* water exposure
- ***In other words: go to where life grabbed a foot-hold & was pickled***

Optimal habitability & preservation: An Example

Sites capturing a phyllosilicate → sulfate transition

- Gale crater, S. Meridiani, Miyamoto

- **Phyllosilicate-dominated strata: Habitable chemistry**
  - Higher a_{H2O} (Generally)
  - Reducing (Fe-phyllosilicates)
  - Circum-neutral pH
  - Prolonged water availability

- **Sulfate-rich strata: Diverse preservation potential**
  - Morphology, isotopic signatures, etc.

- **Capturing the transition:**
  - How did chemistry & climate change?
  - How did life respond?
  - The essence of our understanding of the martian surface

Maximizing Habitability: Syn-depositional Characteristics

Water Activity

Good	**Bad**
Phyllosilicates[a]	Mg-sulfates (all)
Gypsum	Fe^{2+}-sulfates
Carbonates	Na, K-sulfates
	Chlorides (all)
	Fe^{3+}-sulfates[b]

Redox

Good	**Bad**
Fe^{2+}-phyllosilicates[c]	Fe^{3+}-sulfates
Siderite	Fe^{3+}-oxides

pH

Good	**Bad**
Phyllosilicates	Fe^{3+}-sulfates[b]
Gypsum[d]	"Ochreous" Fe^{3+}-sulfates[e]
Mg-sulfates[d]	Fe^{2+}-sulfates[f]

*Temporal availability of water**

Good	**Bad**
Phyllosilicates	--

NOTES:

[a] *In general occur in dilute waters. Many smectites form in saline conditions, thus cannot as yet quantify a_{H2O}*

[b] *Fe^{3+} - sulfates exclusive of "ochreous" phases; include copiapites, rhomboclase, etc. These minerals require both low a_{H2O} and very low pH to form*

[c] *Generally require reducing conditions. In addition, Fe^{3+} - smectites may only form through the oxidation of Fe^{2+} -precursors, suggesting they originally require reducing conditions*

[d] *These phases alone cannot constrain pH; they are pH-independent*

[e] *Include jarosite and schwertmannite; they are relatively insoluble but need acidic pH to form*

[f] *Do not strictly require low pH, but acidic pH favors their formation and stability through suppression of oxidation kinetics by $O_2(g)$*

* *Much of these constraints may come from sedimentology & in situ textural analysis in addition to geomorphology*